Electron Crystallography, D. L. Dorset, S. Hovmöller, and X. Zou, eds., NATO ASI Series E - Vol. 347, 379-382 (1997).

EFFECTS OF LOCAL CRYSTALLOGRAPHY ON STRESS-INDUCED VOIDING IN PASSIVATED COPPER INTERCONNECTS*

R. R. KELLER
National Institute of Standards and Technology
Materials Reliability Division, 853
325 Broadway
Boulder, CO 80303, U. S. A.

J. A. NUCCI
Cornell University
School of Electrical Engineering, Phillips Hall
Ithaca, NY 14853, U. S. A.

Abstract

We have measured local variations in microtexture and grain boundary misorientation in narrow, passivated copper interconnects, using electron backscatter diffraction. This allowed us to differentiate between the local crystallography associated with voids and that associated with regions remaining intact during thermal treatment, all within the same lines. In general, grain boundaries intersecting voids exhibited structures that provided more favorable kinetic pathways for atom migration than those boundaries present within intact regions of the same line. Specifically, grains near voids showed a locally weaker <111> texture than those in unvoided regions. Boundaries between such grains were more likely to be of twist character and of higher angle character than those in unvoided regions. Such boundaries, when of tilt character, were more likely to have misorientation axes parallel to the film plane. Local variations in crystallography are shown to play an important role in determining interconnect reliability.

1. Introduction

We show in this paper the effects of local variations in thin film crystallography on interconnect reliability. In particular, we consider the crystallographic aspects of microstructural features that are of nearly the same dimensions as interconnect thicknesses and widths, or approximately 1 µm. Such features are believed to play a significant role in determining the susceptibility of metal interconnects to stress-induced voiding and electromigration [1, 2]. Average grain size and texture [3] have been shown to have important effects. Namely, larger grains and stronger fiber texture generally lead to improved reliability. However, localized variations in such microstructural features may be intuitively expected to affect performance more than average structures since interconnect dimensions are now small enough that single grains and grain boundaries often traverse the whole line width or thickness. An example of the importance of local variations was demonstrated by Rodbell et al. [1], where aluminum lines of stronger average texture exhibited poorer reliability than those

Electron Crystallography, D. L. Dorset, S. Hovmöller, and X. Zou, eds., NATO ASI Series E - Vol. 347, 379-382 (1997).

of weaker average texture. Electron backscatter diffraction (EBSD) measurements indicated that voids formed near grains that were oriented significantly away from the <111> texture in the stronger average texture lines. It was suggested that grain-to-grain misorientation differences played a strong role in that behavior. Measurements of local texture variations were also made in copper lines subjected to stress voiding conditions [4, 5]. Results similar to those in reference [1] were obtained, but with greater confidence, since a much larger data set was collected. Namely, grains adjacent to voids showed a wider distribution of orientations about the overall <111> line texture than those in unvoided regions. We discuss in this paper the importance of local crystallography in assessing the reliability of copper lines, relying on the results described in references [5, 6].

2. Experimental

2.1. INTERCONNECT FABRICATION

The specimens consisted of copper lines, 0.75 to 2.0 µm in width, and 0.5 µm in height, deposited by electron-beam evaporation onto thermally-oxidized silicon substrates. A 50 nm layer of tantalum was used as both an adhesion layer and a diffusion barrier, encasing the copper lines. The overlying passivation layer consisted of 1.2 µm of SiO_2. Samples were annealed in vacuum for 1 h at 400˚C after passivation, to induce thermal stresses upon cooldown to room temperature. The passivation layer was removed by reactive ion etching in order to expose the bare copper surfaces for subsequent examination.

2.2. ELECTRON BACKSCATTER DIFFRACTION ANALYSIS

We used an EBSD system in a scanning electron microscope (SEM) to collect crystallographic information from the surfaces of the copper lines. EBSD patterns were collected with each specimen at a 70.5˚ tilt towards a low-light, silicon-intensified target camera. The SEM was operated at 30 kV, with probe currents in the range 0.25 to 0.75 nA. For the capture of each pattern, we averaged 64 frames and performed a flat field correction by normalizing the raw pattern to an image containing no crystallographic information. The sampling area of the copper was of approximate diameter 0.2 µm, which enabled analysis of linewidths as small as 0.75 µm. The data collection scheme consisted of placing the electron beam into arrays of positions on the copper lines, and capturing the diffraction patterns. We distinguished between beam positions immediately adjacent to stress voids and those within regions of the specimens that remained intact after thermal processing, as shown in figure 1. A total of 94 diffraction patterns were collected near voids, and 132 patterns were collected from intact regions. The data were analyzed in terms of (111) pole figures and misorientation angle distributions, also called Mackenzie plots.

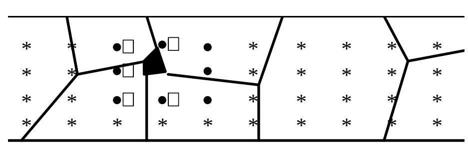

Figure 1. Electron beam positions. Circles represent positions adjacent to voids. Stars are positions in intact regions.

Electron Crystallography, D. L. Dorset, S. Hovmöller, and X. Zou, eds., NATO ASI Series E - Vol. 347, 379-382 (1997).

3. Results and Discussion

3.1. LOCAL TEXTURES AND GRAIN BOUNDARY STRUCTURES

Pole plot distributions calculated from orientation distribution functions revealed texture strength differences between data from voided and unvoided regions. Grain orientations near voids showed an approximately 25% weaker texture than those in unvoided regions. Vapor-deposited metal films often develop a columnar grain structure, where grain boundary planes are inclined nearly perpendicular to the film plane. In such cases, a perfect texture necessarily requires that all grain boundaries be tilt boundaries, with misorientation axes lying normal to the film plane. We refer to such boundaries as tilt-A boundaries. A schematic of such a boundary is shown in figure 2(a). Deviation from perfect textures leads to two other types of boundaries, twist and tilt-B. Twist boundaries are those with misorientation axis lying in the film plane and normal to the boundary plane, as shown in figure 2(b). Tilt-B boundaries are those with misorientation axis lying in the film plane, and in the boundary plane, as seen in figure 2(c). These boundary structures determine local diffusivities within the film plane. The tilt-A struc-

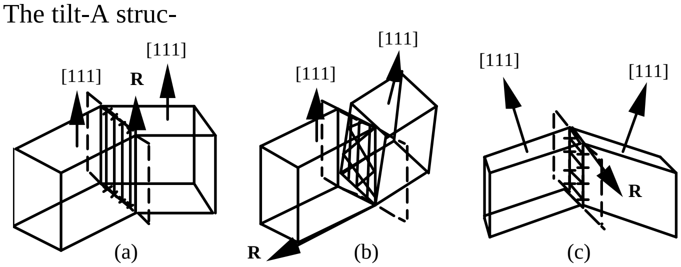

Figure 2. Grain boundaries, with misorientation axes **R** in a thin film. Film plane lies normal to **R** of left figure for each case. Cube edges represent lattice axes. (a) tilt-A boundary, (b) twist boundary, (c) tilt-B boundary.

ture allows atoms to migrate easily via grain boundary diffusion through the boundary, in a direction parallel to the film. The twist and tilt-B structures allow rapid diffusion through grain boundaries, in the film plane, with the tilt-B structure being the most efficient. In terms of void growth, the twist and tilt-B boundaries are expected to lead to more rapid growth than the tilt-A boundary. The net effect of local texture variations is to create a distribution of grain boundary structures, each with a different diffusivity. A further effect is due to misorientation angle. Grain boundaries intersecting voids showed, on the average, a higher misorientation angle than those in unvoided regions. This result can be interpreted in terms of the total number of dislocations within a boundary. Higher angles suggest more dislocations, and therefore greater diffusivities, in general. The characteristic (high diffusivity) boundary associated with voids is then one of twist or tilt-B character, combined with high misorientation angle.

3.2. STRESS VOIDING CONTRASTED WITH ELECTROMIGRATION

The most favorable configuration for rapid stress void growth at a triple junction is a structure with high diffusivity in many in-plane directions. An example is a triple junction consisting of three twist or tilt-B boundaries. Conversely, the most favorable configuration for rapid electromigration void growth is a structure that creates an atomic flux divergence during electron flow. An example is a triple junction consisting of the intersection of tilt-A and non-tilt-A boundaries, with the tilt-A boundaries

Electron Crystallography, D. L. Dorset, S. Hovmöller, and X. Zou, eds., NATO ASI Series E - Vol. 347, 379-382 (1997).

positioned "upstream" with respect to electron flow. A line microstructure favorable for stress void growth might not necessarily be favorable for electromigration void growth. Figure 3 illustrates schematically the requirements for growth in these two cases. The local grain boundary crystallography will be the determining factor for rapid void growth. Real microstructures consist of mixtures of tilt and twist boundaries, so distinction between the favorable cases for stress voiding and electromigration will not be quite as clear.

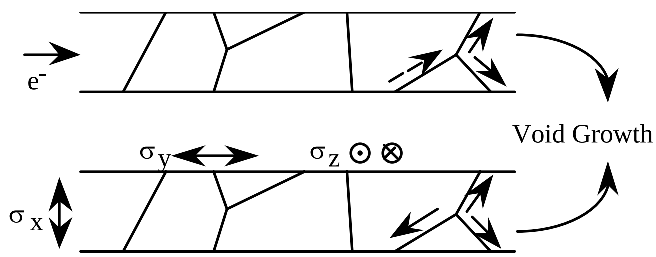

Figure 3. Boundary structures favorable for void growth. Top: electromigration with both low- and high-diffusivity boundaries, amidst high density electron flow. Bottom: stress voiding with three high diffusivity boundaries amidst triaxial tensile stresses.

4. Summary

We have used electron backscatter diffraction to investigate effects of local variations in the crystallography and texture of thin film lines on stress voiding. Voids formed in regions of locally weaker texture. The effects were attributed to variability in grain boundary structures and diffusivities. The variation in boundary structure has different effects for stress voiding as compared to electromigration.

5. References

1. Rodbell, K. P., Hurd, J. L., and DeHaven, P. W. (1996) Blanket and Local Crystallographic Texture Determination in Layered Al Metallization, in H. J. Frost, M. A. Parker, C. A. Ross, and E. A. Holm (eds.), *Polycrystalline Thin Films: Structure, Texture, Properties and Applications II,* Mater. Res. Soc. Symp. Proc. Vol. 403, Mater. Res. Soc., Pittsburgh, pp. 617-626.
2. Sanchez, Jr., J. E., Randle, V., Kraft, O., and Arzt, E. (1992) Morphology and crystallography of electromigration induced transgranular slit failures in aluminum alloy interconnects, *Submicrometer Metallization: The Challenges, Opportunities, and Limitations,* SPIE Vol. 1805, SPIE, Bellingham, WA, pp. 222-231.
3. Knorr, D. B. and Rodbell, K. P. (1993) Effect of Line Width on Electromigration of Textured Pure Al Films, in K. P. Rodbell, W. F. Filter, H. J. Frost, and P. S. Ho (eds.), *Materials Reliability in Microelectronics III,* Mater. Res. Soc. Symp. Proc. Vol. 309, Mater. Res. Soc., Pittsburgh, pp. 345-350.
4. Field, D. P., Nucci, J. A., and Keller, R. R. (1996) Interconnect Failure Dependence on Crystallographic Structure, *Proc. 22nd Int'l Symp. for Testing and Failure Analysis*, ASM International, Metals Park, OH, pp. 351-355.
5. Nucci, J. A., Keller, R. R., Sanchez, Jr., J. E., and Shacham-Diamand, Y. (1996) Local crystallogra-phic texture and voiding in passivated copper interconnects, *Appl. Phys. Lett.* **69,** 4017-4019.
6. Nucci, J. A., Keller, R. R., Field, D. P., and Shacham-Diamand, Y. (1997) Grain boundary misorientation angles and stress-induced voiding in oxide passivated copper lines, *Appl. Phys. Lett.* **70**, 1242-1244.